ESTIMATES OF DOSES FROM GLOBAL FALLOUT

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Abstract—This paper summarizes information about external and internal doses resulting from global fallout and presents preliminary estimates of doses resulting from intermediate fallout in the contiguous United States. Most of the data on global fallout were extracted from the reports of the United Nations Scientific Committee on the Effects of Atomic Radiation, in which the radiation exposures from fallout have been extensively reviewed at regular intervals. United Nations Scientific Committee on the Effects of Atomic Radiation estimated the average effective doses received by the world's population before 2000 to be about 0.4 mSv from external irradiation and 0.6 mSv from internal irradiation, the main radionuclide contributing to the effective dose being ^{137}Cs. Effective doses received beyond 2000 result mainly from the environmentally mobile, long-lived ^{14}C and amount to about 2.5 mSv summed over present and future generations. Specific information about the doses from fallout received by the United States population is based on the preliminary results of a study requested by the U.S. Congress and conducted jointly by the Centers for Disease Control and Prevention and the National Cancer Institute. Separate calculations were made for the tests conducted at the Nevada Test Site and for the high-yield tests conducted mainly by the United States and the former Soviet Union at sites far away from the contiguous United States (global tests). The estimated average doses from external irradiation received by the United States population were about 0.5 mGy for Nevada Test Site fallout and about 0.7 mGy for global fallout. These values vary little from one organ or tissue of the body to another. In contrast, the average doses from internal irradiation vary markedly from one organ or tissue to another; estimated average thyroid doses to children born in 1951 were about 30 mGy from Nevada Test Site fallout and about 2 mGy from global fallout.
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INTRODUCTION

THE TESTING of nuclear weapons in the atmosphere was the most significant cause of exposure to the world population to man-made environmental sources of radiation (UNSCEAR 2000). The practice continued from 1945 through 1980 (Table 1). Depending on the location of the explosion (altitude and latitude), the radioactive debris resulting from the nuclear weapons tests were partitioned among the local, regional, and global environments to various degrees. Portions of the radioactive debris were deposited at or near the site of the test (local fallout), regionally up to several thousand kilometers downwind (intermediate fallout), and throughout the world (global fallout). This paper summarizes information about the doses resulting from global fallout and presents preliminary estimates of doses resulting from intermediate fallout in the contiguous United States. Doses from local fallout are presented separately in this issue by Simon and Bouville (2002).

Global fallout was produced mainly by the high-yield tests detonated by the United States and Russia in the 1950's and early 1960's. Because of the huge energy liberated during those tests, most of the radioactive debris they produced was transported into the stratosphere, then gradually descended to Earth's surface in a matter of months or years; during that time, the activities of the short-lived radionuclides substantially decreased, so that most of the doses are due to long-lived radionuclides with half-lives of 1 y or more. During transit from the stratosphere to the ground, the radioactive debris was diluted primarily over the entire latitude band into which it was injected. However, wet processes (e.g., rain, snow) are much more efficient than dry processes (sedimentation, impaction, or diffusion) to scavenge the atmosphere so that the deposition density over a month or a year is approximately proportional to the amount of precipitation during that time. For global fallout, the amounts of radionuclides deposited per unit area of ground and per unit of precipitation are relatively constant in a given latitude band, so that using measurements carried out anywhere in the world is justified as a first approximation to derive doses for the population of the latitude band that is considered. Every few years, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has reviewed doses from global fallout, based on the measurements of radionuclides deposited on soil. Most of the information presented in this paper is

Table 1. Number[a] and total yields of atmospheric nuclear weapons tests carried out by each country (UNSCEAR 2000).

Country	Time period	Number of tests	Total yield (MT)
United States	1945–1962	195	154
Russia	1949–1962	219	247
United Kingdom	1952–1958	21	8
France	1960–1974	45	10
China	1964–1980	22	21
Total	1945–1980	502	440

[a] Excludes 39 safety shots (22 from the United States, 12 from the United Kingdom, and 5 from France) and 2 operational drops in Japan.

extracted from recent UNSCEAR reports (UNSCEAR 1982, 1993, 2000).

Doses from intermediate fallout are more difficult to estimate than those from global fallout because the deposition pattern of fallout in the intermediate zone depends on the yield of the test considered and on the meteorological conditions at the time of the test, and it is much less homogeneous than that of global fallout. Each test should be considered separately. Such an exercise has been carried out in a U.S. Department of Health and Human Services (DHHS) study mandated by the U.S. Congress (DHHS 2001). The estimated doses received by the United States population as a result of intermediate fallout from tests conducted at the Nevada Test Site (NTS) will be presented in this paper and compared with the dose estimates from global fallout (DHHS 2001).

METHODS FOR ASSESSING DOSES FROM GLOBAL FALLOUT

The most important radionuclides, from the dosimetric point of view, that were produced and globally

dispersed in atmospheric nuclear testing are listed in Table 2 by order of increasing radioactive half-life (UNSCEAR 2000). Most of these radionuclides are isotopes of solid elements at normal temperature; when released into the atmosphere, they quickly attach to natural aerosols or to bomb debris and behave like particulate material. Once deposited on Earth's surface, only a small fraction is transferred into the human food chain before returning to Earth's surface, which is an effective sink for those radionuclides. Exceptions are ^3H and ^{14}C, which participate in the global water and carbon cycles, respectively, and are recycled into the biosphere until they decay. The methods used to assess doses from ^3H and ^{14}C will be discussed separately.

UNSCEAR has developed models to predict the doses from global fallout resulting from each of the more important pathways of exposure to humans (external irradiation from radionuclides deposited on soil, ingestion and inhalation). Those pathways are illustrated in Fig. 1 along with the transfer coefficients used to describe the relations of time-integrated concentrations or dose in successive compartments. As an example, P_{23} is the time-integrated concentration (Bq d L^{-1} or Bq d kg^{-1}) of a radionuclide in diet divided by the deposition density (Bq m^{-2}) of the same radionuclide on soil.

For radionuclides that are not recycled into the biosphere, the UNSCEAR methods of dose estimation are based on measured activities of radionuclides that deposited on Earth's surface (Table 2). The fraction of the activity released into the atmosphere that contributes to global fallout increases with the radioactive half-life of the radionuclide considered because most of the global fallout results from radioactive debris that was injected into the stratosphere from which it gradually descended to Earth's surface in a matter of months to years; during

Table 2. Global fallout: activities (PBq) of radionuclides released in the atmosphere and deposited on Earth's surface (based on UNSCEAR 2000).

Radionuclide	Half-life	Release, A_0 (PBq)	Activity deposited (PBq)	Deposition/release	Population-weighted deposition density, F (Bq m^{-2})
^{131}I	8.0 d	675,000	5,300	0.008	15,000
^{140}Ba	13 d	759,000	9,900	0.013	28,000
^{141}Ce	33 d	263,000	7,900	0.030	23,000
^{103}Ru	39 d	247,000	9,900	0.040	28,000
^{89}Sr	51 d	117,000	5,600	0.048	16,000
^{91}Y	59 d	120,000	7,900	0.066	23,000
^{95}Zr	64 d	148,000	9,900	0.067	28,000
^{144}Ce	280 d	30,700	11,500	0.37	40,000
^{54}Mn	310 d	3,980	1,300	0.33	4,800
^{106}Ru	370 d	12,200	5,900	0.48	21,000
^{55}Fe	2.7 y	1,500	910	0.59	3,300
^{125}Sb	2.8 y	740	540	0.73	1,900
^3H	12 y	186,000	—[a]	—	—
^{241}Pu	14 y	140	140[b]	1[b]	450
^{90}Sr	29 y	622	612	0.98	2,000
^{137}Cs	30 y	948	919	0.97	3,000
^{14}C	5,700 y	213	—[a]	—	—
^{240}Pu	6,600 y	4.35	4.35[b]	1[b]	14
^{239}Pu	24,000 y	6.52	6.52[b]	1[b]	21

[a] Not applicable because the deposited activity is recycled into the environment.
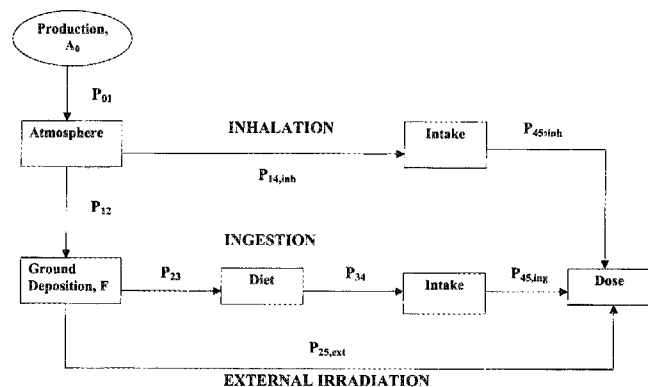[b] The deposited activity is assumed to be equal to the release.

Fig. 1. Pathways of exposure to humans considered by the United Nations Scientific Committee on the Effects of Atomic Radiation.

that time, the activities of the short-lived radionuclides substantially decreased.

To calculate the average doses from fallout over the entire world's population, UNSCEAR took the distribution of the population according to latitude band into account and estimated the world average population-weighted deposition density, F (Bq m^{-2} weighted by proportion of total population in the latitude band), for each major radionuclide that was not recycled into the atmosphere. The results, calculated using the factors recommended by UNSCEAR (2000), are presented in Table 2.

The methods used to estimate doses from global fallout resulting from each important pathway of exposure to humans are discussed in turn.

External irradiation from radionuclides deposited on soil

The external effective dose commitment, $E_{C,ext}(i)$, for a specific radionuclide, i, released in an atmospheric test is

$$E_{C,ext}(i) = F(i) \times P_{25,ext}(i) \qquad (1)$$

where $F(i)$ is the deposition density of radionuclide i and $P_{25,ext}(i)$ is the transfer coefficient from soil to dose from external irradiation. The values of $P_{25,ext}(i)$ have been calculated by multiplying the dose-rate conversion coefficients for radionuclides deposited on the soil derived from Beck (1980) by the mean lifetime of the radionuclide and by an average factor accounting for air to tissue dose conversion and for indoor occupancy in buildings (80% time indoors was assumed, with a shielding factor of 0.2). The latter factor is 0.7 Sv Gy^{-1} (effective dose rate per unit absorbed dose in air) times 0.36 (0.2 outdoor occupancy plus 0.8 indoor occupancy times 0.2 building shielding). For short-lived radionuclides (all except ^{137}Cs), the dose-rate conversion coefficient for a plane source has been used. For ^{137}Cs, the dose-rate conversion coefficient applying to an exponential concentration profile in the ground of mean depth 3 cm has been used. The indoor occupancy, as well as the shielding factor, can vary a great deal among different populations and is a source of uncertainty in the calculations of external

dose. Also, the different behavior of radionuclides deposited in urban and rural environments has not been taken into account.

The values of the $P_{25,ext}(i)$ transfer coefficients that are used to estimate external doses from deposited radionuclides from fallout from nuclear testing are presented in Table 3. The annual contributions to doses following a single deposition event can easily be derived from the $P_{25,ext}$ values because they depend only on the radioactive decay of the radionuclides.

Inhalation

The effective dose commitment from inhalation, $E_{C,inh}(i)$, for a specific radionuclide i released in an atmospheric test is

$$E_{C,inh}(i) = A_0(i) \times P_{01}(i) \times P_{14} \times P_{45,inh}(i)$$
$$= [F(i)/P_{12}] \times P_{14} \times P_{45,inh}(i)$$
$$= F(i) \times P_{25,inh}(i), \qquad (2)$$

where $A_0(i) \times P_{01}(i)$ is the time-integrated air concentration (Bq y m^{-3}) of radionuclide i at ground level, P_{14} is the breathing rate (m^3 y^{-1}), and $P_{45,inh}(i)$ is the effective dose coefficient (Sv Bq^{-1}) for inhalation. To determine the time-integrated air concentration, measurements are required for the entire time that radionuclides remained in air. Because this is usually not achieved in practice, the time-integrated air concentration is often obtained as the less precise quotient of the deposition density $F(i)$ (Bq m^{-2}) and of P_{12}, which is the effective deposition velocity (m y^{-1}).

Table 3. Global fallout: values of transfer coefficients P_{25} relating the effective dose (nSv) to the deposition density on soil (Bq m^{-2}) (UNSCEAR 1993, 2000).

| Radionuclide | Half-life | P_{25} (nSv per Bq m^{-2}) | | |
		External irradiation	Inhalation	Ingestion
^{131}I	8.0 d	0.1	0.17	4.3
^{140}Ba	13 d	0.093	0.14	0.013
^{141}Ce	33 d	0.048	0.034	0.05
^{103}Ru	39 d	0.42	0.033	—
^{89}Sr	51 d	—	0.16	0.08
^{91}Y	59 d	—	0.18	—
^{95}Zr	64 d	2.87	0.104	0.10
^{144}Ce	280 d	0.2	1.3	0.52
^{54}Mn	310 d	4.02	0.02	1.4
^{106}Ru	370 d	1.19	1.7	—
^{55}Fe	2.7 y	—	0.0043	2
^{125}Sb	2.8 y	6.54	0.045	2.5
^{3}H	12 y	—	—[a]	—[a]
^{241}Pu	14 y	—	12	0.19
^{90}Sr	29 y	—	4.6	53
^{137}Cs	30 y	97.2	0.11	55
^{14}C	5,700 y	—	—[a]	—[a]
^{240}Pu	6,600 y	—	840	180
^{239}Pu	24,000 y	—	840	180

[a] Not applicable because the deposited activity is recycled into the environment.

The average value of P_{12} varies with the precipitation rate at different locations and with the chemical and physical nature of the radionuclide considered. For global average calculations, the average value of P_{12} for particulate material deposited after atmospheric nuclear testing has been estimated to be 5.56×10^5 m y^{-1} on the basis of measurements in New York City over several years (Bennett 1978).

The transfer coefficient from deposition on the ground to effective dose from inhalation, $P_{25,inh}(i)$, is calculated as $P_{14} \times P_{45}(i)/P_{12}$. Values of the $P_{25,inh}(i)$ transfer coefficients are presented in Table 3 (UNSCEAR 1993, 2000).

Ingestion

The effective dose commitment from ingestion, $E_{C,ing}(i)$ for a specific radionuclide, i, released in an atmospheric test is

$$E_{C,ing}(i) = F(i) \times P_{23}(i) \times P_{34} \times P_{45,ing}(i)$$
$$= F(i) \times P_{25,ing}(i) , \quad (3)$$

where $F(i)$ is the deposition density of radionuclide i and $P_{25,ing}(i)$ is the transfer coefficient from soil to dose from ingestion. The values of $P_{25,ing}(i)$ vary from one radionuclide to another and have been primarily derived from extensive series of measurements of fallout radionuclides in soil, diet, and body carried out in the 1960's and 1970's (UNSCEAR 1982, 1993, 2000). Values of the $P_{25,ing}(i)$ transfer coefficients are presented in Table 3 (UNSCEAR 1993, 2000).

Specific methods for tritium and ^{14}C

The radionuclides ^{3}H and ^{14}C require special attention because of their high mobility in the environment and the fundamental nature of water and carbon cycles in the biosphere. After its release, ^{3}H is transformed into HTO and follows the global water cycle. A seven-compartment model was used for estimating global tritium doses (NCRP 1979). The seven compartments include the atmosphere, surface soil water, deep ground water, surface streams and fresh water lakes, saline water and inland seas, ocean surface, and deep ocean. Transfers between compartments are quantified using rate constants that are based on the known rates of water movement from processes such as precipitation, evapotranspiration, and runoff. The concentration of tritium in humans is calculated from an average of the concentrations in the sources of water ingested, assumed to be 33% from the atmosphere, 53% from surface fresh waters, 13.3% from groundwater, and 0.7% from ocean surface water (through fish) (NCRP 1979). The estimated world average effective dose per unit release of tritium, P_{05}, is 0.06 nSv PBq^{-1}.

After ^{14}C is released, it is distributed among the various reservoirs of the global carbon cycle: the atmosphere, the terrestrial biosphere, the hydrosphere, and the lithosphere. In its 2000 report, UNSCEAR based its assessment of the global doses from ^{14}C on the work of

Titley et al. (1995). Their model includes 21 compartments: atmosphere, woody tree parts, nonwoody tree parts, ground vegetation, decomposers, soil, Antarctic Ocean (four layers), Atlantic Ocean (four layers), Pacific and Indian Oceans (three layers), Arctic Ocean (two layers), ocean sediments, and a compartment representing input from fossil fuel burning. An effective dose commitment per unit release of ^{14}C, P_{05}, of 10,900 nSv PBq^{-1} is calculated with the assumptions that the future world population stabilizes at 10^{10} people and that the global inventory of stable carbon does not increase from its present value.

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For the radionuclides that are not recycled in the biosphere, the effective dose commitments to the world's population are estimated using eqns (1) through (3) for external irradiation, inhalation, and ingestion, respectively. The parameter values needed to estimate the effective dose commitments are the deposition densities, $F(i)$, given in Table 2, and the transfer coefficients from soil to dose, P_{25}, which are provided in Table 3. Results are presented in Table 4. For all of those radionuclides, except ^{125}Sb, ^{90}Sr, and ^{137}Cs, the doses are estimated to have been delivered by 2000.

For the radionuclides that are recycled in the biosphere, ^{3}H and ^{14}C, the effective dose commitments to the world's population are estimated as the products of the release, A_0, presented in Table 2 and of the doses per unit release, P_{05}, given in previous paragraphs. Results also are presented in Table 4. Because of the very long half-life of ^{14}C, and of its mobility in the environment, most of the dose from ^{14}C will be delivered in the future. The effective dose commitment from ^{14}C is much greater than that from any other radionuclide, but it is delivered at relatively small dose rates over thousands of years. Thus, the listed dose is intergenerational and not to a single person.

The effective doses from global fallout, broken down by pathway of exposure and by time period, are shown in Table 5. Ingestion is the predominant pathway of exposure in any time period considered, followed by external irradiation, and then inhalation. Beyond 2,200, ^{14}C remains the only contributor to the effective dose, if a small component due to external irradiation from ^{137}Cs is ignored.

UNSCEAR (2000) has provided detailed information on the contributions of the major radionuclides to the annual effective doses for the time period between 1945 and 2000. With respect to external irradiation (Fig. 2), the short-lived radionuclide ^{95}Zr, together with its decay product ^{95}Nb, was the main contributor to the annual dose during the period of active testing (1950's and early 1960's). Of less significance were ^{106}Ru, ^{54}Mn, and ^{144}Ce. Beginning in 1966, ^{137}Cs became the most important contributor to the annual dose from external irradiation and presently is the only radionuclide contributing to

Table 4. Estimates of average effective doses (μSv) from global fallout received by the world's population (UNSCEAR 1993, 2000).

Radionuclide[a]	Estimated average effective doses (μSv) from global fallout received:					
	before 2000				from 2000 to 2100	beyond 2100
	External irradiation	Inhalation	Ingestion	All pathways	All pathways	All pathways
[131]I	1.6	2.6	64	68	----	—
[140]Ba	27	0.4	0.5	28	----	—
[141]Ce	1.1	0.8	—	1.9	----	—
[103]Ru	12	0.9	—	13	—	—
[89]Sr	—	2.6	1.9	4.5	----	----
[91]Y	—	4.1	—	4.1	—	—
[95]Zr	81	2.9	—	84	—	----
[144]Ce	7.9	52	—	60	—	....
[54]Mn	19	0.1	—	19	—	—
[106]Ru	25	35	----	60	----	----
[55]Fe	----	0.01	6.6	6.6	----	—
[125]Sb	12	0.1	—	12	0.003	—
[3]H	----	—	24	24	0.1	—
[241]Pu	—	5	—	5	—	—
[90]Sr	—	9.2	97	106	8.6	0.02
[137]Cs	166	0.3	154	320	124[b]	13[c]
[14]C	—	----	144	144	120	2,230
[240]Pu	—	13	—	13	—	----
[239]Pu	—	20	—	20	—	—
All	353	149	492	994	253	2,243

[a] The dose estimates include the contributions from the decay products.
[b] Including 114 μSv from external irradiation and 10 μSv from ingestion.
[c] Including 12.7 μSv from external irradiation and 0.5 μSv from ingestion.

Table 5. Estimated average effective doses from global fallout (μSv) received by the world's population over different time periods (UNSCEAR 2000).

Time period	Effective dose (μSv) resulting from:			
	External irradiation	Ingestion	Inhalation	All pathways of exposure
1945–1999	353	492	149	994
2000–2099	114	139	—	253
2100–2199	11.4	51	—	62
>2200	1.3	2,180	—	2,181
Total	480	2,860	149	3,490

continuing external exposure from deposited radionuclides.

For the inhalation pathway (Fig. 3), the doses have been assumed to be delivered in the same year the deposition occurred. They were, therefore, highest during active atmospheric testing and dropped rapidly once it ceased in 1980. Important contributors to inhalation doses were [144]Ce, the transuranic radionuclides, [106]Ru, [91]Y, [95]Zr, and [89]Sr.

The components of the annual dose through the ingestion pathway from radionuclides that do not recycle in the biosphere are illustrated in Fig. 4. The more significant contributors to the annual dose were ^{90}Sr and [137]Cs. During active atmospheric testing, ^{137}Cs was more
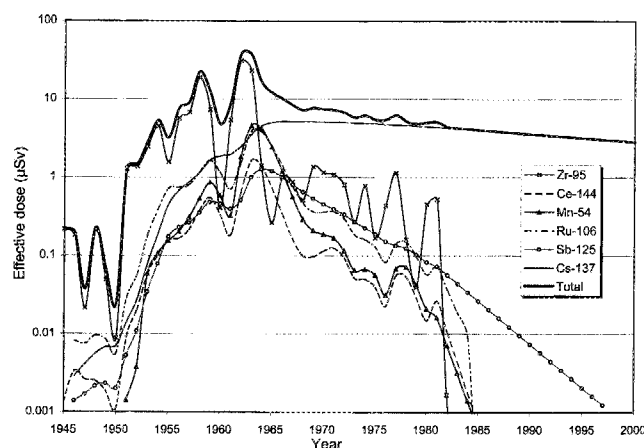
Fig. 2. Global fallout: estimated average annual effective doses to the world population from external irradiation (UNSCEAR 2000).

important than ^{90}Sr because of its more immediate transfer to diet and delivery of dose. Beginning in 1967, ^{90}Sr became the most important contributor to the annual dose because of its substantial transfer to vegetation through root uptake and its longer retention in the body.

The annual doses through ingestion from the globally dispersed ^{3}H and ^{14}C are shown separately in Fig. 5. The annual doses from ^{3}H decrease relatively rapidly at the end of the period of active testing because of its
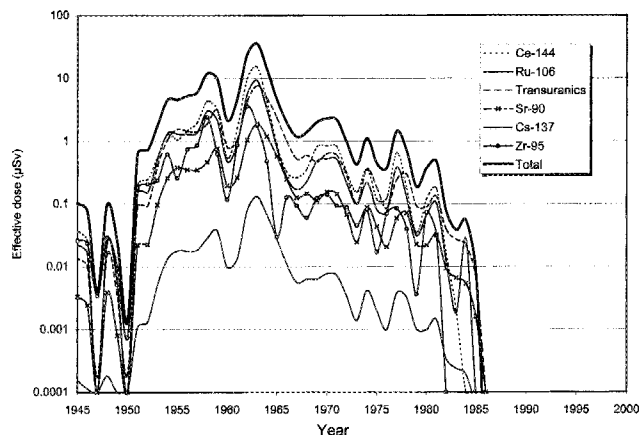
Fig. 3. Global fallout: estimated average annual effective doses to the world population from inhalation (UNSCEAR 2000).
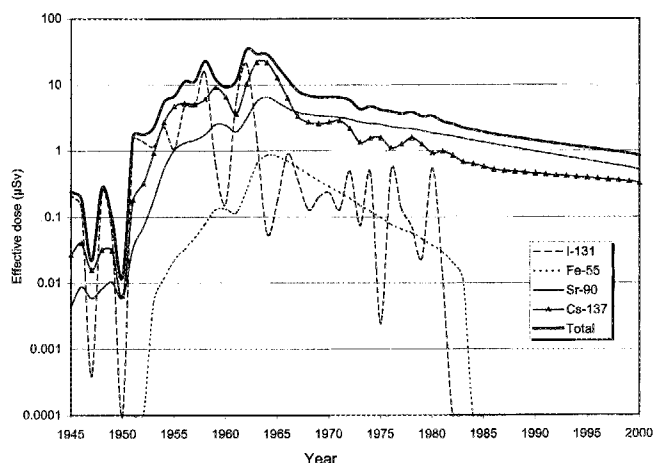

Fig. 4. Global fallout: estimated average annual effective doses to the world population from ingestion (UNSCEAR 2000).

Fig. 5. Global fallout: estimated average annual effective doses to the world population from globally distributed ^{3}H and ^{14}C (UNSCEAR 2000).

Fig. 6. Global fallout: estimated average annual effective doses to the world population from the main pathways of exposure to humans (UNSCEAR 2000).

radioactive decay and its gradual dilution into the ocean. Unlike the case for ^{3}H, the annual doses from ^{14}C have remained relatively stable since the 1970's.

The estimates of the total annual effective doses delivered before 2000, as well as the contributions from the main pathways, are illustrated in Fig. 6. The highest annual effective dose, 110 μSv, occurred in 1963; since then, the annual doses have declined to about 6 μSv in the 1990's. About 70% of the dose delivered before 2000 was received from 1951 through 1970. On average, from 1945 through 2000, external irradiation and ingestion (excluding ^{3}H and ^{14}C) contributed almost equally to the dose.

Finally, the relative importance of the physical and chemical characteristics of the major radionuclides contributing to global fallout can be estimated from a rough assessment of the fractions of the activities released that were deposited on Earth's surface or incorporated in the body through inhalation or ingestion. The calculation of the intakes was restricted to 1945 through 2000, and the
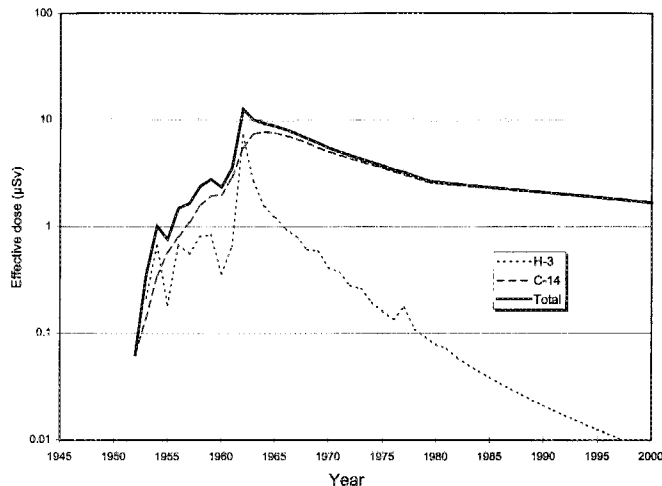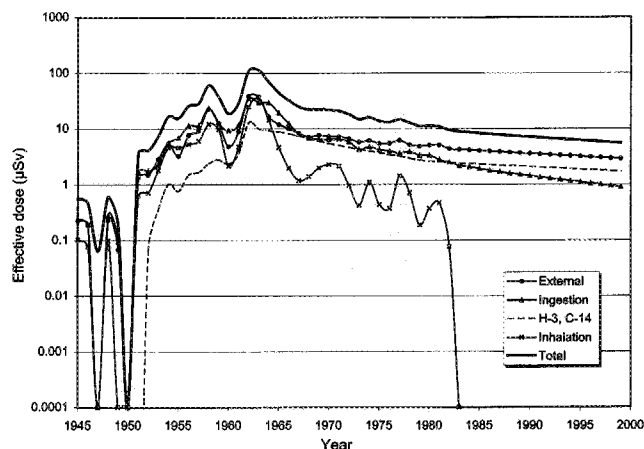
world population was assumed to be 5×10^9 during that time. Results are presented in Table 6. For the radionuclides that are not recycled in the biosphere, the fraction of activity released that is deposited on Earth's surface, f_1, depends only on the radioactive half-life and is as low as 0.008 for ^{131}I. It is only for radioactive half-lives longer than about 10 y that the activity deposited is about equal to the activity released. The fraction of deposited activity that was inhaled by the world's population, $f_{2,inh}$, is estimated to be 2×10^{-7} for all radionuclides because the deposition velocity is assumed to be radionuclide-independent. However, the fraction of the deposited activity that was ingested by the world's population, $f_{2,ing}$, varies within a wide range from one radionuclide to another according to radioactive half-life and effectiveness of transfer from deposition to foodstuffs. The parameter $f_{2,ing}$ is estimated to be as low as 7×10^{-8} for ^{140}Ba and as high as

Table 6. Estimation of the fractions of the activities released that are deposited and taken in the body via inhalation or ingestion.

Radionuclide	Half-life	Deposition/Release	Intake/Deposition		Intake/Release	
			Inhalation	Ingestion	Inhalation	Ingestion
^{131}I	8.0 d	0.008	2×10^{-7}	1×10^{-6}	1×10^{-9}	8×10^{-9}
^{140}Ba	13 d	0.013	2×10^{-7}	7×10^{-8}	2×10^{-9}	9×10^{-10}
^{141}Ce	33 d	0.030	2×10^{-7}	—	6×10^{-9}	—
^{103}Ru	39 d	0.040	2×10^{-7}	—	8×10^{-9}	—
^{89}Sr	51 d	0.048	2×10^{-7}	5×10^{-7}	9×10^{-9}	2×10^{-8}
^{91}Y	59 d	0.066	2×10^{-7}	—	1×10^{-8}	—
^{95}Zr	64 d	0.067	2×10^{-7}	—	1×10^{-8}	—
^{144}Ce	280 d	0.37	2×10^{-7}	—	9×10^{-8}	—
^{54}Mn	310 d	0.33	2×10^{-7}	—	8×10^{-8}	—
^{106}Ru	370 d	0.48	2×10^{-7}	—	1×10^{-7}	
^{55}Fe	2.7 y	0.59	2×10^{-7}	2×10^{-4}	1×10^{-7}	1×10^{-5}
^{125}Sb	2.8 y	0.73	2×10^{-7}	—	2×10^{-7}	—
^{3}H	12 y	—^{a}	—^{a}	—^{a}	.....	4×10^{-5}
^{241}Pu	14 y	1^b	2×10^{-7}	—	2×10^{-7}	—
^{90}Sr	29 y	0.98	2×10^{-7}	3×10^{-5}	2×10^{-7}	3×10^{-5}
^{137}Cs	30 y	0.97	2×10^{-7}	6×10^{-5}	2×10^{-7}	6×10^{-5}
^{14}C	5,700 y	—^{a}	—^{a}	—^{a}	—	6×10^{-3}
^{240}Pu	6,600 y	1^b	2×10^{-7}	—	2×10^{-7}	.....
^{239}Pu	24,000 y	1^b	2×10^{-7}	—	2×10^{-7}	—

^{a} Not applicable because the deposited activity is recycled into the environment.
^{b} The deposited activity is assumed to be equal to the release.

2×10^{-4} for ^{55}Fe. The fraction of activity released that is either inhaled or ingested, $f_{3,inh}$ or $f_{3,ing}$, was also estimated. Both fractions are the products of f_1 and of $f_{2,inh}$ or $f_{2,ing}$; for comparison purposes, the values for ^{3}H and ^{14}C have been estimated as well, although they may include some recycled activities. All values of $f_{3,ing}$ are fairly small, but they range widely, from 9×10^{-10} for ^{140}Ba to 6×10^{-3} for ^{14}C.

ESTIMATES OF DOSES FOR THE POPULATION OF THE CONTINENTAL UNITED STATES

In 1998, the U.S. Congress requested that DHHS assess the feasibility and public health implications of a detailed study of the health impact on the United States population of radioactive fallout from the testing of nuclear weapons worldwide. In response to that request, the Centers for Disease Control and Prevention and the National Cancer Institute (NCI) collaborated to calculate preliminary estimates of doses and health risks from exposure to radioactive fallout from the most important nuclear weapons tests conducted from 1951 through 1962 at NTS, as well as at other sites throughout the world (DHHS 2001). Although the report prepared for the U.S. Congress is still in draft, and its results are preliminary, the methodology that was used to obtain the dose estimates, as well as some of the results, are germane to this discussion and hence are presented here.

Preliminary dose estimates for representative persons in all counties of the contiguous United States have been calculated in the DHHS (2001) study for the first time for the most important radionuclides produced from nuclear weapons testing between 1951 and 1963 by the United States and other nations. Estimates of doses received during 1951 through 2000 (called "lifetime doses" in the DHHS report) were calculated separately for two groups of hypothetical persons in each county of the contiguous United States: those who were adults in 1951, and those who were born on 1 January 1951. In the DHHS feasibility study, particular attention was given to the dose estimates for the thyroid gland and for the red bone marrow because thyroid diseases and leukemia were presumed to be the most important health effects resulting from exposures to radioactive fallout. Doses were estimated separately for the tests conducted at NTS and for the tests conducted at other sites throughout the world (global testing), primarily for the following three reasons: (1) the data available for estimating fallout were not of the same type for the tests conducted at NTS and for the global tests, so different methods had to be used; (2) fallout from the two sources resulted in dissimilar geographic patterns of deposition of radioactivity across the contiguous United States; and (3) the relative importance of the various radionuclides was not the same for the tests conducted at NTS and for the global tests, resulting in differences in the relative importance of the doses by organ.

DOSES TO THE UNITED STATES POPULATION RESULTING FROM NEVADA TEST SITE FALLOUT

One hundred officially reported nuclear tests were conducted in the atmosphere at NTS (DOE 1994). Those tests ranged in yield from extremely small explosions (<1 ton equivalent TNT) to a maximum size of 74 KT (Shot Hood on 5 July 1957). The total energy yield of the nuclear tests conducted at NTS was about 1 MT—very small compared with the total energy yield of 440 MT for

all tests conducted over the world (Table 1). These mostly low-yield tests produced radioactive materials that remained essentially in the lower atmosphere (troposphere) and deposited a large fraction of their activity on the territory of the contiguous United States during the first passage of the radioactive cloud. Because most, if not all, of the energy produced by NTS tests resulted from fission, the production of the globally distributed ^{3}H and ^{14}C was minimal and is not considered in this section.

Not all of the tests conducted at NTS produced fallout that was detectable or measured beyond the confines of the test site. In the DHHS (2001) report, doses have been estimated for the 61 more significant events: 8 in 1951 (Ranger and Buster-Jangle series), 8 in 1952 (Tumbler-Snapper series), 11 in 1953 (Upshot-Knothole series), 13 in 1955 (Teapot series), 19 in 1957 (Plumbbob series), and 2 in 1962 (Storax series). Those 61 tests, which accounted for over 95% of the total ^{131}I produced (NCI 1997), contributed almost all of the radiation exposure delivered to the American people.

Two pathways of exposure to humans have been considered: (1) external irradiation resulting from the activities deposited on the ground, and (2) internal irradiation from ingestion of contaminated foodstuffs. For both pathways, the doses were derived from the estimation of the activities deposited on a unit area of ground (deposition densities, Bq m^{-2}).

Estimates of deposition density were developed for a range of important radionuclides, for each of the approximately 3,000 counties within the contiguous United States and for each of the 61 tests that were considered (DHHS 2001). In general, tests at NTS were conducted within a few days of one another, so that appropriate environmental radiation measurements could distinguish individual tests. For the purposes of the DHHS feasibility study, the estimates of deposition density for the radionuclides under consideration were derived from the ^{131}I deposition densities reported in NCI (1997), which had been based primarily on daily measurements from the gummed-film network operated by

the Atomic Energy Commission (AEC) Health and Safety Laboratory (now known as the U.S. Department of Energy Environmental Measurements Laboratory). Because the measurement sites were few compared with the large number of counties, the deposition densities at locations nearby to the measurement sites were estimated through the use of mathematical interpolation procedures (NCI 1997). Extrapolating data to locations without measurements is one of the inherent and unavoidable limitations of those calculations. The deposition densities of nuclides other than ^{131}I were calculated from NTS ^{131}I deposition density values by using the relations calculated by Hicks (1981, 1990) for each NTS test.

The resulting geographic pattern of deposition of ^{137}Cs in the United States, for all tests conducted at NTS, is presented in Fig. 7. The deposition densities generally decrease with distance from NTS to the east, the predominant wind direction across the continental United States. There was little deposition in the states west of NTS. The estimates of the average amount of ^{137}Cs deposited in United States counties range from well below 200 Bq m^{-2} to about 1,300 Bq m^{-2}. In the western United States, deposition resulted primarily from dry processes, because the tests were intentionally conducted under such meteorological conditions that heavy fallout resulting from rainfall should not occur in the vicinity of NTS. However, in the eastern United States, the regional and local variations of deposition density resulted primarily from local variations in precipitation. The well-known area in northern New York State with elevated deposition was due to heavy thunderstorm activity during passage of the cloud from test SIMON in April 1953 (Beck et al. 1990; NCI 1997). The total deposition of ^{137}Cs from all NTS tests considered in this report through 1962 is estimated to be 2.3 PBq, the years of greatest deposition being 1952, 1953, and 1957. Deposition estimates for ^{137}Cs and for other important radionuclides are presented in Table 7. Because a large fraction of the activities produced during the tests was deposited within a few days after the detonation, the deposition estimates
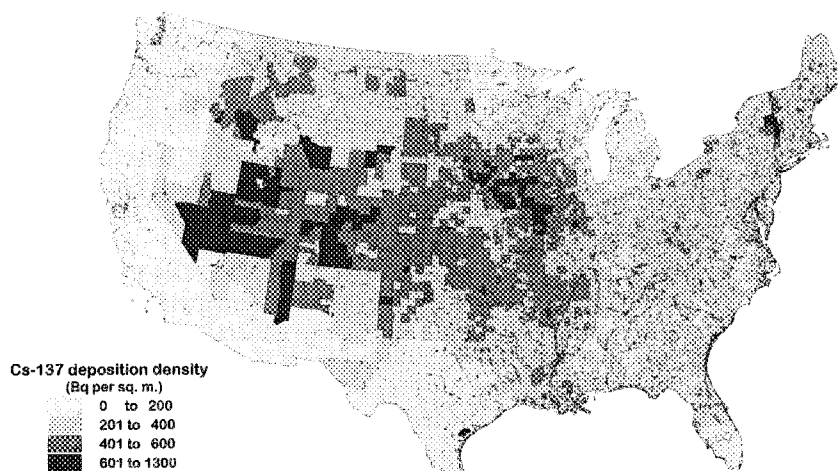

Fig. 7. ^{137}Cs deposition density in the United States from all tests conducted at the Nevada Test Site (DHHS 2001).

Table 7. Activities (PBq) of radionuclides released in the atmosphere by NTS and global tests, and deposited in the contiguous United States (DHHS 2001).

Radionuclide	Half-life	Activity deposited (PBq) in the U.S.	
		NTS tests	Global tests
^{131}I	8.0 d	1,500	110
^{140}Ba	13 d	1,400	290
^{141}Ce	33 d	500	220
^{103}Ru	39 d	430	210
^{89}Sr	51 d	330	170
^{95}Zr	64 d	220	310
^{144}Ce	280 d	40	300
^{106}Ru	370 d	24	160
^{90}Sr	29 y	1.8	19
^{137}Cs	30 y	2.3	28

for short-lived radionuclides like ^{131}I and ^{140}Ba are much more important than those for long-lived radionuclides like ^{90}Sr and ^{137}Cs.

Dose estimates from external irradiation

Effective doses from external irradiation were estimated for each of the NTS tests that were considered and for all counties of the contiguous United States. To simplify the feasibility calculations, two approximations were made: (1) the external dose to organs like the thyroid and bone marrow were taken to be numerically equal to the effective dose, and (2) external doses were assumed to be age-independent. The first of those approximations stems from the fact that the external doses to most tissues and organs are about the same, primarily because the gamma ray energies emitted from many radionuclides in fallout are energetic enough to completely penetrate the body. Hence, it is justified to make an approximation that the effective dose (expressed in millisievert) is numerically equal to the absorbed dose (expressed in milligray) for most organs. With regard to the second approximation, calculations using computer models of the human body indicated that the effective dose to young children is about 10 to 30% higher (NCRP 1999) than for adult, though that difference is believed to be small compared with the overall uncertainties of the dose estimates. In the DHHS (2001) report, the lifetime doses from external irradiation were therefore considered the same for people who were either adults or small children in 1951.

Even though a large number of fission products are produced in a nuclear explosion, only a few account for most of the external exposure. Different radionuclides contribute significantly to the dose rate at different times, and thus the relative importance of the various radionuclides varies according to the length of time for the fallout to arrive at the location of exposure. At early arrival times after each test (within a few hours), ^{132}Te—^{132}I contribute substantially to the exposure; after a few days, ^{140}Ba—^{140}La, ^{95}Zr—^{95}Nb, and ^{103}Ru are more important. Later (months to years), ^{137}Cs is the dominant contributor to the dose rate from external irradiation.

The dose received by individuals depends on the time they spent outdoors while the fallout was on the ground, and on the extent to which radionuclides penetrate into the soil with passing time. In the DHHS (2001) report, the doses from external irradiation were estimated using assumptions and parameter values similar to those used by UNSCEAR (2000). Results are presented in Table 8. The average lifetime dose received by the United States population from external irradiation resulting from NTS tests is estimated to be about 0.5 mGy, the more important contributors being ^{140}Ba—^{140}La, ^{132}Te—^{132}I, and ^{95}Zr—^{95}Nb. The most exposed individuals probably lived in states immediately downwind from NTS. However, smaller areas of higher and lower doses from external irradiation occurred throughout the United States because of the uneven deposition of fallout and the variation in directions taken by the clouds containing the radioactive fallout. Residents of some counties near NTS received doses in excess of 3 mGy, and residents of the extreme western and northwestern states and some midwestern counties received average doses less than 0.25 mGy.

The numerical values of dose provided in the DHHS (2001) report are estimates for hypothetical individuals living permanently in each county. How close the doses that are provided are to the actual dose received by any real person living there depends on many factors, primarily how similar the assumptions in the calculations are to an individual's lifestyle over the time the exposure was received. Many factors about each member of the public, such as age and lifestyle, might result in his or her exposure differing from the estimates provided in the DHHS (2001) report. The actual dose from external irradiation from NTS fallout would generally range from about one fourth as large as the estimates provided here to about four times larger than those estimates. In some specific locations and time, the range of possible doses at a single location might be even larger.

Dose estimates from internal irradiation

The doses from internal irradiation resulted mainly from inhalation of contaminated air and ingestion of contaminated foodstuffs. In the DHHS (2001) report, only the doses from ingestion, which are generally much greater than those from inhalation, were estimated. The method of calculation of the doses from ingestion was derived from that developed and used by the Off-Site Radiation Exposure Review Project (ORERP), which was performed from 1979 through 1987 (Church et al. 1990). The ORERP study was designed to calculate doses from NTS tests that were received by people living in the near downwind regions.

The general ORERP method is described in detail in Appendix E of the DHHS report (Anspaugh 2000a) and is briefly presented here. It is conceptually similar to the method used by UNSCEAR (2000), but it is markedly more complex because the processes involved in the estimation of the radionuclide concentrations in foodstuffs and of the intakes by humans were studied in more

Table 8. Summary of preliminary thyroid and red bone marrow doses (mGy) from Nevada Test Site and global fallout received as a result of exposure to the most important radionuclides. The values are averages for adults residing in the contiguous United States at the time of the tests, unless otherwise specified. Blank spaces reflect very small values.

Radionuclide	Half-life	NTS fallout			Global fallout		
		Thyroid or red bone marrow external dose (mGy)	Thyroid internal dose (mGy)	Red bone marrow internal dose (mGy)	Thyroid or red bone marrow external dose (mGy)	Thyroid internal dose (mGy)	Red bone marrow internal dose (mGy)
^{3}H	12.3 y					0.07	0.07
^{14}C	5,730 y					0.1	0.1
^{54}Mn	313 d				0.04		
^{89}Sr	52 d		0.001	0.03			
^{90}Sr	28.5 y			0.02		0.0009 [0.002]a	0.2 [0.5]a
^{95}Zr-^{95}Nb	64 d	0.08			0.2		
^{97}Zr-^{97}Nb	17 h	0.02					
^{103}Ru	39 d	0.03			0.02		
^{106}Ru	368 d		0.001	0.002	0.04		
^{125}Sb	2.7 y				0.03		
^{131}I	8 d	0.02	5 [30]a	0.001		0.4 [2]a	0.00009 [0.0002]a
^{132}Te-^{132}I	3.3 d	0.1	0.06	0.001			
^{133}I	0.9 d	0.02	0.04				
^{136}Cs	13 d		0.002	0.002			
^{137}Cs	30 y	0.01	0.009	0.009	0.3	0.1	0.1
^{140}Ba-^{140}La	13 d	0.2		0.006	0.05		
^{144}Ce	284 d				0.02		
^{239}Np	2.4 d	0.02					
Rounded totals: - Adults; - Child born 1 January 1951.		0.5	5 [30]a	0.1	0.7	0.7 [2]a	0.6 [0.9]a

a Values in brackets are for a child born 1 January 1951.

detail. The ORERP method includes the following:

- Estimating the total amount of an individual radionuclide that might be ingested by humans of differing ages. This simple statement covers a complex undertaking of estimating the dynamics of radionuclide contamination of foods and age-dependent human-consumption rates of food (Whicker and Kirchner 1987); and
- Estimating the dose at each age that a member of the public would receive from ingesting a single unit of activity of a particular radionuclide.

The formulation developed by the ORERP project, in simple form, can be expressed by the following equation:

$$D = F_0 \times I \times D_c, \qquad (4)$$

where

D = absorbed dose, Gy, or effective dose, Sv, for the radionuclide of interest;

F_0 = deposition density of the radionuclide of interest at time-of-fallout arrival, Bq m^{-2};

I = integrated intake by ingestion of the radionuclide per unit deposition density, Bq per Bq m^{-2};

D_c = ingestion dose coefficient for the radionuclide, Gy Bq^{-1} or Sv Bq^{-1}.

Doses from internal irradiation resulting from ingestion of contaminated foodstuffs were calculated from the deposition density estimates derived for the 61 NTS tests under consideration, each important radionuclide in fallout, and for each county of the contiguous United States. In a first step of the calculations, seasonally dependent values of the radionuclide concentrations in important foodstuffs (milk, meat, leafy vegetables, root vegetables, and grain products) were estimated by mathematically based environmental transfer models (Whicker and Kirchner 1987). Those models account for the ecological behavior of radionuclides by considering the initial retention of fallout by vegetation, the loss of radionuclides from vegetation, dilution of radionuclide concentration in fresh vegetation by plant growth, uptake of radionuclides through the soil-root system, and recontamination of plant surfaces by resuspension and by rain splash. As expected, the foodstuff concentrations of many radionuclides were estimated to have occurred in the early summer months when garden and farm food production would have been highest. The models used by ORERP were developed to simulate the transfer of radionuclides to foodstuffs in areas close to NTS. The

DHHS (2001) report recognizes that some of the parameter values used by ORERP are not strictly applicable to other regions of the United States where precipitation patterns and agricultural practices differ substantially from those encountered in areas close to NTS. This is only one of many known uncertainties.

Age-dependent consumption rates of foodstuffs were used in the ORERP method, along with estimates of the average value of the fraction of foods produced locally, to estimate the radionuclide activities ingested from the contaminated foodstuffs. Finally, mathematical models simulating the behavior of radionuclides in the gastrointestinal tract, uptake of radionuclides by the gastrointestinal tract, and the subsequent absorption and retention of radionuclides in the various organs and tissues of the body, were used to estimate the thyroid and bone marrow doses. As mentioned, doses were estimated to representative persons who were adults in 1951 or born in 1951.

Estimates of doses from internal irradiation to the thyroid and red bone marrow, averaged over the United States population for all NTS tests, are presented in Table 8. The average thyroid doses are estimated to be about 5 mGy for persons who were adults in 1951 and about 30 mGy for persons who were born in 1951. Most of the thyroid dose was due to the consumption of milk contaminated with ^{131}I. The counties receiving greater internal thyroid doses from NTS fallout were, in general, in Nevada and in Utah because of their close proximity to NTS and because they were normally downwind of the test site, while the counties receiving the lowest internal doses were in states of Pacific Northwest, primarily Washington and Oregon. County-specific dose estimates for children (born 1 January 1951) range from <0.1 mGy in less than 10 counties, to as high as 300 mGy in over 550 counties. In general, thyroid doses for adults were estimated to be 10 times lower. The estimates assume average consumption rates of fresh cow's milk. Higher thyroid doses would have been received by people consuming higher than average amounts of fresh cow's milk or goat's milk.

The average bone-marrow doses were estimated to be about 0.1 mGy either for persons who were adults in 1951 or for those who were born in 1951. Most of the bone-marrow dose resulted from ingestion of foodstuffs contaminated with ^{89}Sr and ^{90}Sr. Similar to the situation for the thyroid doses, the counties receiving greater internal bone-marrow doses from NTS fallout were primarily in Nevada and in Utah because of their close proximity to NTS and because they were generally downwind of the test site, while the counties receiving the lowest bone-marrow doses were in the Pacific Northwest, primarily Washington and Oregon.

DOSES TO THE UNITED STATES POPULATION RESULTING FROM GLOBAL FALLOUT

The population of the contiguous United States also received doses resulting from nuclear weapons tests conducted at sites other than NTS (called "global" tests

in this paper). In the DHHS (2001) report, the tests conducted by the United States and the United Kingdom, mainly in the Pacific, and by Russia, mainly at Novaya Zemlya, from 1949 through 1962 have been considered. The total explosive yield of those atmospheric tests amounted to about 410 MT (Table 1). The tests conducted by France and China from 1960 through 1980, which altogether accounted for 7% of the total energy yield, were not considered.

The fallout that occurred in the contiguous United States from the global tests resulted mainly from high-yield tests (greater than 1 MT), which accounted for the release of over 90% of the activity of the fission products, and injected most of their debris into the stratosphere (UNSCEAR 1982, 1993). Those high-yield tests were detonated mainly in 1958, 1961, and 1962. Because of the long residence times of air in the stratosphere and its relatively slow transfer to the troposphere (on the order of one year), it was not possible to assign the results of environmental radiation measurements made at ground level to any particular test (Table 1). More importantly, however, because of the long delay between production and ground deposition, the fallout from the high-yield tests was relatively depleted in short-lived radionuclides.

Although a huge body of literature exists regarding fallout from nuclear weapons tests, the only widespread continuous monitoring of fallout deposition was the global networks of precipitation collectors (stainless-steel pots and ion-exchange columns) operated by the AEC's Health and Safety Laboratory (HASL) and the network of air sampling stations along the 80th meridian operated before 1963 by the Naval Research Laboratory and after 1963 by HASL (Lockhart et al. 1965; Harley 1976). The most important radionuclide deposition density data that are available for global fallout are the monthly ^{90}Sr deposition density measurements reported by the HASL for about 30 sites across the United States (HASL 1958–1972; ERDA 1977). Those data were collected primarily because ^{90}Sr at that time was considered the most significant health hazard from global fallout because of its chemical similarity to calcium and its consequential incorporation in bone after ingestion of contaminated foodstuffs as well as because of its long physical and biological half-life. The number of ^{90}Sr monitoring sites varied from year to year with the maximum number in operation during 1962 to 1965. ^{89}Sr also was fairly continuously monitored in global fallout but at fewer sites and times. Other radionuclides, such as ^{95}Zr—^{95}Nb were monitored infrequently and only at a few sites in the United States.

Few or no monitoring data exist for years before 1958. In a separate program, the HASL monitored total deposition of beta-emitters at about 50 sites from 1952 through 1960 using gummed film (see Beck et al. 1990; Beck 1999). However, only the data for limited periods of time following NTS tests have been reevaluated, and thus the gummed film data that would probably be useful

for estimating global fallout were unavailable for use in DHHS (2001).

As for NTS fallout, estimates of deposition density from global tests have been obtained for each county in the contiguous United States and for each important radionuclide that contributed substantially to the radiation exposure. The deposition densities were estimated on a monthly basis from 1953 through 1972. Although much of the fallout from NTS tests, particularly in areas close to NTS, fell to the ground without any accompanying rainfall, most of the debris from global fallout was deposited by precipitation, which tended to effectively wash the debris from the lower altitudes after the material fell from high altitudes. Thus, the deposition density of fallout in each county was closely related to the frequency and intensity of rain, particularly during the months when fission products were at their peak concentration in the lower atmosphere.

To estimate the monthly deposition density of ^{90}Sr in each county of the contiguous United States, the deposition density in any particular county was assumed to be proportional to the precipitation that occurred in that county during that month. Because the deposition density per unit precipitation varied significantly with latitude and longitude (Beck 2000), a model describing that variation was developed.

This crude model for deposition density of global fallout does not account for deposition under dry weather conditions. This is generally not a large error because the fallout under such conditions was probably less than 10% of the total deposition. Not accounting for dry deposition would incur a larger error in the more arid regions of the United States. Although the model used to estimate the ^{90}Sr deposition density is fairly crude, a comparison with the available data for a number of sites where sufficient data are available indicates that the agreement was fairly good (Beck 2000).

Because of the sparseness of environmental measurement data on deposition of most radionuclides in global fallout, a mathematical model that describes the global circulation patterns that control the dispersion of fallout was used to estimate the activity ratios of various nuclides to ^{90}Sr deposition for periods when no data were available (Bennett 1978). The model predicts well the variation of ^{90}Sr deposition over time (UNSCEAR 2000). However, the estimates of the deposition density of the shorter-lived nuclides such as ^{131}I are much less precise because of the very small number of environmental measurement data that could be used to calibrate the model. The deposition density of each of the radionuclides listed in Table 7 was estimated for each county and month by multiplying the estimated ^{90}Sr deposition density for that county and month by the ratios of isotopes predicted by the model for that month. The estimates for the more important contributors to external dose, ^{95}Zr—^{95}Nb and ^{137}Cs are probably reasonable because: (1) ^{95}Zr was measured in precipitation or air at several sites in 1958 and 1961–1962 and ^{89}Sr was measured at a relatively large number of sites (HASL 1958–1972), and (2) the activity ratio of ^{137}Cs to ^{90}Sr in fallout is relatively constant.

The total deposition of ^{137}Cs from global fallout from 1953 through 1972 is shown in Fig. 8. In general, the lowest values of deposition density occurred in the western, more arid United States. The area of the country east of the Mississippi River to the eastern seaboard was relatively uniform in the amount of ^{137}Cs deposited by global fallout. This contrasts with the deposition density of NTS fallout (Fig. 7), which generally declined with increasing distance from NTS.

Table 7 gives the calculated total depositions of each radionuclide from global fallout (1953 to 1972) and compares those with the estimates for NTS fallout. Table 7 shows that the deposition of long-lived radionuclides from global fallout is about a factor of 10 to 15 greater than that from NTS fallout. However, the total deposition
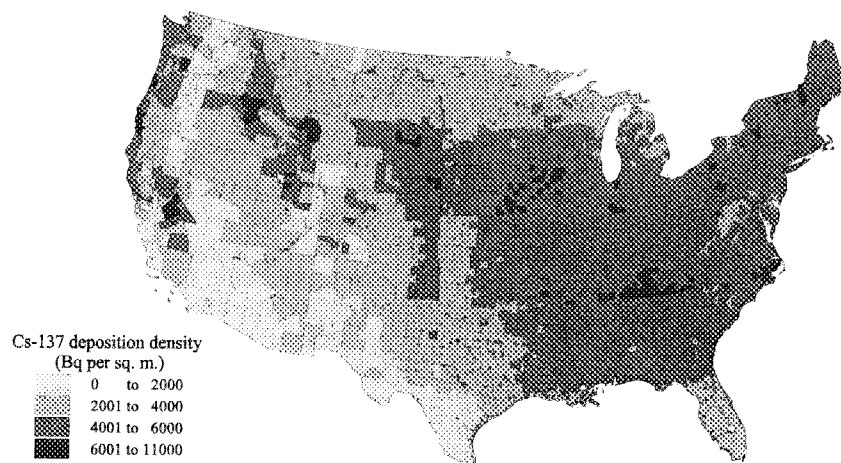

Cs-137 deposition density
(Bq per sq. m.)
0 to 2000
2001 to 4000
4001 to 6000
6001 to 11000

Fig. 8. ^{137}Cs deposition density in the United States from global tests conducted by the United States and by other nations (DHHS 2001).

of short-lived nuclides such as ^{131}I was much less for global fallout than for NTS fallout.

Global tests also produced large amounts of ^{3}H and [14]C. Because ^{3}H and ^{14}C enter their respective environmental pools and cycle in the environment according to their own chemical properties, they do not deposit in the same manner as do radionuclides associated with more insoluble fallout particles. Hence, the usual methods of calculating deposition density are not appropriate. The doses from ^{3}H and ^{14}C were calculated separately, using methods similar to those used by UNSCEAR (1993, 2000), which are briefly discussed in the first part of this paper.

Estimates of dose from external irradiation

As for external dose from NTS fallout, it was assumed that the absorbed dose to the red bone marrow and the thyroid (expressed in milligray) is numerically equal to the effective dose (expressed in millisievert) and that there is no age dependency in the conversion factors from exposure rate to effective dose rate. The same methods and parameter values were used to estimate the doses from external irradiation from NTS or from global fallout.

The estimated average dose for the United States population from global fallout was 0.7 mGy (Table 8), with little variation across the United States; in general, estimated external doses received were 1 mGy or less. The highest annual per capita doses occurred in 1962 and 1963 and were comparable to the annual per capita doses from NTS fallout in 1952, 1953, 1955, and 1957. However, the average lifetime dose from global fallout was about 50% higher than that from NTS fallout.

In contrast to the doses from NTS fallout, very short-lived radionuclides such as [132]Te—[132]I were insignificant contributors to the lifetime dose from global fallout. About 70% of the lifetime dose from global fallout resulted from [95]Zr—[95]Nb and to [137]Cs. In contrast, ^{137}Cs contributed only a small amount (about 2%) of the dose from NTS fallout.

Estimates of dose from internal irradiation

As for the case of NTS fallout, only the ingestion doses from global fallout, which are generally greater than those from inhalation, were considered in the DHHS (2001) report. Different methods of dose estimation were used for the five radionuclides likely contributing the largest exposures (^{3}H, ^{14}C, ^{90}Sr, ^{131}I, and ^{137}Cs).

Ingestion doses from ^{90}Sr and ^{137}Cs originating in global fallout were estimated by a methodology similar to that used for radionuclides from NTS fallout. Monthly average values of the integrated intake were derived from Whicker and Kirchner (1987), using the values of deposition density of ^{90}Sr and of ^{137}Cs previously calculated on a county-by-county basis over each month for 1953 through 1972. Age-dependent dose coefficients (ICRP 1998) for the general public were used to convert intake to dose. Doses to thyroid and to bone marrow were calculated on a county-by-county basis for adults and for

a representative person assumed to be born on 1 January 1951.

For the case of exposure to ^{131}I in global fallout, only approximate average values of deposition density were estimated for the contiguous United States as a whole, because reliable calculations were not possible on a county-by-county basis (DHHS 2001). Age-dependent integrated intake values were derived from the ORERP calculations. Dose coefficients were taken from the ICRP (1998), and calculations were made of average doses over the entire population of the contiguous United States for adults and for persons assumed to be born on 1 January 1951.

Doses for ^{3}H and ^{14}C, two globally dispersed radionuclides, were calculated on the basis of the specific activity approach, which differs considerably from the methods used for other radionuclides that depend on first estimating deposition density.

Doses from ^{3}H were calculated with the use of the NCRP (1979) model, which simulates the world's hydrological cycle through the use of seven compartments consisting of atmospheric water, surface soil water, deep groundwater, surface streams and fresh water lakes, saline lakes and inland seas, ocean surface, and the deep ocean. The use of the hydrological cycle is appropriate because most of the ^{3}H released is in the form of tritiated water or is soon converted to that form in soil. Calculations also consider the specific activity of ^{3}H in the various water compartments and the rate of change among the compartments. Doses from ^{3}H were assumed to be independent of age and of geographic location over the northern hemisphere and to be numerically equal for thyroid and bone marrow.

The assessment of dose from ^{14}C is particularly difficult because of its long half-life of 5,730 y. To calculate doses over the first 50 y from the release of ^{14}C, which provide the estimates of lifetime doses, a compartment model for the global circulation of carbon was used. The model chosen was that of Titley et al. (1995), which is the latest model that has been widely accepted and that builds on previously accepted models. The model takes into account temperature changes, photosynthesis in the surface layers of the oceans, and transfers of carbon down the water column. As for ^{3}H, doses from ^{14}C were assumed to be independent of age and of geographic location over the northern hemisphere, and to be numerically equal for thyroid and bone marrow.

Estimates of doses from internal irradiation to thyroid and red bone marrow, averaged over the United States population for global tests, are presented in Table 8. The average thyroid doses are estimated to be 0.7 mGy for persons who were adults in 1951 and 2 mGy for persons who were born in 1951. Most of the thyroid dose resulted from ingestion of milk contaminated with [131]I. At this time, no information can be provided on the geographic variation of the thyroid dose from global fallout. This was one of the most important limitations of the DHHS feasibility report.

Estimated average bone-marrow doses are about 0.6 mGy for persons who were adults in 1951 and 0.9 mGy for those who were born in 1951. The geographic pattern of bone-marrow doses reflects the pattern of ^{137}Cs deposition density from global fallout shown in Fig. 8, with the highest values, up to 3 mGy for children, expected to have occurred in the eastern United States.

The average doses estimated here agree well with the doses published by UNSCEAR (1993) for the 40° to 50° latitude band that includes part of the United States. In addition, data presented to the U.S. Congress by Terrill (1963) on concentrations of radionuclides in milk were used to perform calculations useful for validating the assumptions and models used in this report. The different sets of results agree with each other (Anspaugh 2000b).

DISCUSSION

Because the purpose of the DHHS (2001) report was only to determine feasibility, there was no intention to develop new tools or to gather all data needed to complete an extensive study of doses to Americans from nuclear weapons tests conducted by the United States and other nations. Instead, preliminary doses were calculated on the basis of a detailed review of a limited number of reports and using available dose-assessment models. In some cases, particularly for the doses resulting from the intake of shorter-lived radionuclides (e.g., ^{131}I) in global fallout, the doses calculated may have considerable error. Future work would improve the precision of those calculations. Although the computed county-specific deposition densities and related doses are uncertain, deposition maps (Figs. 7 and 8) are useful to illustrate general spatial patterns of fallout exposure across the United States.

As examples of results from the DHHS (2001) study, doses averaged over the contiguous United States are summarized in Table 8. Because the thyroid and red bone marrow are among the most radiosensitive organs and tissues of the body, their doses were selected as examples for presentation. Thyroid cancer, noncancer thyroid disease, and leukemia, which arises from the red bone marrow, are health effects that would be studied if a more detailed evaluation is conducted.

The estimated average total internal doses from global fallout are considerably smaller for the thyroid but greater

for the red bone marrow than those from NTS fallout, whereas the doses from external irradiation are similar for NTS and for global fallout (Table 8). However, the comparative magnitude of the doses from both sources of fallout varies according to geographic location and body organ being considered. Additionally, the mixture of radionuclides contained in fallout differs for the two sources of fallout (Table 8). As a result of those differences, the temporal and geographic distributions of doses from NTS and from global fallout differ substantially. For the nuclear weapons tests conducted at NTS, fallout occurred predominantly in the western states surrounding NTS; the short-lived radionuclides, identified by a short half-life (Column 2 in Table 8), were key components of NTS fallout and the highest doses to Americans resulted from [131]I. In contrast, global fallout exposures were higher in areas with high-precipitation rates, such as the eastern states. At those locations, the long-lived radionuclides, such as ^{137}Cs and ^{90}Sr, were much more abundant in global fallout than in NTS fallout.

The role played by the large differences in time delays and distances between the sites of production and ground deposition for NTS tests and the global tests is illustrated in Table 9. For NTS tests, this time delay averages a few hours to a few days, while for global fallout it is of the order of 1 y. For a long-lived radionuclide like ^{137}Cs, the differences in time delays do not affect substantially the extent to which radioactive decay occurs between production and deposition; however, because the site of ground deposition is much further away for global tests than for NTS tests, the dilution of the activity released is much greater and the fraction of the activity deposited to that released is lower by a factor of 10 for the global tests than for the NTS tests (Table 9). Nevertheless, because the activity of ^{137}Cs released by global tests was more than 100 times greater than that of NTS tests, the dose from ^{137}Cs was higher for global tests than for NTS tests. In comparison, for a short-lived radionuclide like ^{131}I, the fraction of the activity deposited to that released was lower by a factor of 1,500 for global tests than for NTS tests, and the dose from ^{131}I was lower for global tests than for NTS tests, even though the global tests released 100 times more ^{131}I than the NTS tests (Table 9).

Table 9. Estimation of the fractions of the activities of ^{137}Cs and ^{131}I released that are deposited and ingested into the body.

Activity or fraction	[137]Cs		[131]I	
	NTS	Global tests	NTS	Global tests
Release (PBq)	8	948	5,600	675,000
Deposition (PBq)	2.3	28	1484	112
Intake by ingestion (TBq)	0.13	1.8	1.9	0.15
Deposition/Release	0.3	0.03	0.3	0.0002
Intake by ingestion/Deposition	6×10^{-5}	6×10^{-5}	1×10^{-6}	1×10^{-6}
Intake by ingestion/Release	2×10^{-5}	2×10^{-6}	3×10^{-7}	2×10^{-10}

CONCLUSION

During the last few years, global doses resulting from fallout from nuclear weapons tests have received renewed attention. In the latest UNSCEAR (2000) report, estimates are provided for the first time of average annual effective doses received by the world's population from 1945 through 2000, broken down by pathway of exposure to humans and radionuclide.

Also, as a result of a request by the U.S. Congress, preliminary estimates of dose from global fallout have been derived for each county of the contiguous United States for the most important long-lived radionuclides. The comparison with the doses resulting from tests conducted at NTS illustrates the differences between intermediate range and global fallout. Doses from global fallout result mainly from long-lived radionuclides and are strongly associated with rainfall amounts, thus being greater, on average, in the eastern United States. In contrast, intermediate range fallout from tests conducted at NTS led to doses mainly due to short-lived radionuclides and generally decreasing with distance from the explosion site. Altogether, average doses from external irradiation received by the population of the contiguous United States were on the order of 1 mGy for any organ and tissue of the body. Doses from internal irradiation were highest for the thyroid. They averaged about 6 mGy for adults in 1951 and about 30 mGy for persons born in 1951. Thyroid doses received by specific individuals are expected to have varied widely according to age, place of residence, and dietary habits.

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